

THE REACTIVITIES OF SUSPENSIONS OF COALS
IN STEAM AT 900 - 950° C. (1,700° F.)

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Investigators generally agree that the reaction of steam with various types of carbon and cokes, which has been widely investigated at the Morgantown Coal Research Center of the Bureau of Mines (5) and elsewhere, (3) (7) (8) (9) (10) (14) (15) (16) (18) is related to the reaction of steam with coal. Despite this relationship, knowledge of the kinetics of the steam-carbon reaction does not disclose nor reveal the kinetic behavior of coals of various rank and type in coal gasifiers. The conclusions drawn from studies of the reactivities of various types of carbon furnish little or no information on process rates, which can be used in the design of improved types of commercial coal gasification equipment.

Several investigators (2) (11) (12) (13) studied the kinetics of the reactions of coals, generally with air, oxygen or carbon dioxide, but restricted their research to relatively low temperatures, specific types of coals, fixed beds of coarse particles, etc. Others tried to fit theoretical rate equations to data from large-scale gasifiers, modifying their constants accordingly. Attempts to extrapolate these results to other types of coals suspended or entrained in steam at considerably higher temperatures and pressures (4) have never proved satisfactory and, in many cases, have failed. It is doubtful that a generally applicable rate equation can be established for substances as complex structurally and as widely different in composition as coals of various rank, type or grade. Generalization for all types of coals, cokes or chars, or the use of questionable assumptions to extend the applicability of a rate equation to all gasification conditions does not seem justified.

A "falling particle" technique has been developed by Dotson and Holden (5) of the Bureau of Mines at Morgantown, W. Va., for the determination of the reaction rates of carbons with steam. The method originally devised for finely divided carbons was recently modified by the authors and developed for the rapid determination of the reactivities of coals. The essential feature of the method is that it closely simulates the conditions existing when powdered coals entrained in steam are gasified in large-scale gasifiers.

The purpose of the work here described was to determine the "relative reactivities" of various types of coals when their particles react with steam at 1,700° F. Specifically, the object was to separate the overlapping effects of thermal decomposition and actual steam-carbon reaction when steam interacts with coals at high temperatures.

"Reactivity" of solid fuels is generally defined (7) as the velocity or time-rate of the reaction between a solid fuel and an oxidizing gas, usually O_2 , CO_2 , or H_2O , under a given set of experimental conditions, including temperature, pressure (4), particle size, size consist, and bulk density. "Relative reactivity" is defined here as the relative rapidity of reaction between a fuel and an oxidizing gas (steam in our case) in a given apparatus under the same set of experimental conditions. It is an experimentally obtained index figure, useful in comparison with other fuels. Pertaining to an average (measured) residence time, the term "relative reactivity"

signifies no more than what the name implies: reactivities of various fuels related to each other. It should not be confused with "kinetic reaction rate."

The term "kinetic reaction rate" is a more fundamental characteristic of a given fuel reacting with a given gas; it is independent of the gasifier design, and is usually more significant from a process engineering standpoint. However, its determination is more time consuming. The kinetic reaction rate usually expresses, in form of a rate equation, the functional relation between reaction rate and reactant concentration at any given temperature and pressure. For maximum usefulness from a design standpoint, full knowledge of the kinetic rate includes the effects of all variables on the reaction rate, particularly temperature and pressure (4) (17), and the physical state of the reactants, such as particle size, size consist, and bulk density. The effects of mass transfer rate and flow pattern, insofar as they affect the overall reaction rate, should also be known.

Although work is being planned on the determination of the kinetic rates of the reaction of steam with coals at higher temperatures and pressures, this paper is restricted to the study of the more rapidly determined relative reactivities of coals (-60 + 65 mesh) interacting with steam at 1,700° F. and atmospheric pressure. The reactivities are expressed in terms of (1) "fuel conversion," given as weight-loss in grams per gram of dry, mineral matter - free coal; or (2) "carbon conversion," shown as grams of carbon gasified per gram of carbon in the coal. In either case, the conversion of the coal to gas is due both to thermal decomposition and reaction with steam.

Apparatus and Experimental Technique

The reactor developed and used to determine the relative reactivities of coals by the falling particle technique is shown schematically in Figure 1. The 3-inch inside diameter 9-foot long alloy steel reactor tube is electrically heated by 9 (pairs) prefabricated semicircular embedded-coil-type heating elements 11.5 inches high and 5 inches outside diameter, each controlled by a variable transformer. Elements at the top and bottom serve to balance the heat losses; the other 7 elements control the temperature in the 85-inch long isothermal zone. Longitudinal temperature profiles or traverses are determined from time to time, and the heat input is adjusted to maintain isothermal conditions.

Doubly distilled water passing through a rotameter is vaporized in a small electrically heated tube, and the steam thus formed is preheated to 800 - 1,000° F. before injection into the reactor. The steam flow-rate is adjusted for the desired steam-to-coal ratio, generally 3 pounds of steam per pound of dry mineral matter - free fuel, and the vibratory feeder is started. The uniformly sized (-60 + 65 mesh per inch) coal particles in the feed bowl move upward along a spiral track until each particle is swept by nitrogen, flowing at a rate of about 1.2 std. cu. ft. per hour, through a hole into the feed-tube and thence into the reactor. The coal feed-rate, generally 50 g. per hour in the reactivity tests described, is controlled by adjusting the voltage input to the vibrating mechanism.

The coal particles, blanketed by nitrogen, fall through a 7-inch long 5/16-inch inside diameter feed-tube, the latter surrounded by a 5/16-inch wide annulus (not shown in Figure 1) through which the steam is passed downward at about 1,000° F. The coal particles thus preheated in the feed-tube are entrained in the steam and enter the top of the reactor-tube through a 1-inch inside diameter circular opening at its center. The entering particles together with steam and nitrogen spread somewhat, but direct contact with the wall is prevented as they are carried downward in laminar flow (conventional Reynolds number about 20) blanketed with gases. Accelerated by gravity, they continue to fall through the steam, nitrogen, and generated gases, virtually at free-falling velocity. Calculated for a reactor temperature of 1,700° F. (900 - 950° C.) and for a low-volatile bituminous coal fed at 50 grams per hour, with

a steam-to-coal ratio of 3:1, the linear velocity of the steam-nitrogen mixture in the upper part of the reactor was 0.19 ft. per sec. As the measured average terminal velocity of the coal particles was 1.33 ft. per sec., the difference is their free-falling velocity: 1.14 ft. per sec.

Since the coal particles travel 6 times faster than the entraining steam-nitrogen mixture, it is clear that the fuel particles fall in the reactor tube almost freely through the gases. The flow, therefore, is not so much of the entrainment type, but is rather an unsteady or partial suspension, and the term "falling particle technique" properly describes it. (An isotope tracer method used to determine the residence time of the fuel particles, and thus their terminal velocity, will be described in another paper to be published by the authors.) Laminar flow inside the reactor prevents direct contact between the particles and the heated reactor tube. Nevertheless, because of the small heat capacity of the fuel particles, and the effective transfer of heat --- partly by radiation from the reactor walls and partly by convection and conduction through the steam medium --- the falling particles are rapidly heated to the isothermal reactor temperature of 1,700° F.

The concentration of fuel particles in the upper part of the reactor, under the conditions stated, is estimated to be about 50 mg per dm³ of reactor volume containing a gas mixture of 85 percent steam and 15 percent nitrogen. On an average, approximately 8 1/2 particles of -60 + 65 mesh coal are in partial entrainment (suspension) at any given time in each cm³ of steam-nitrogen mixture flowing at a rate of 265 cc. per sec. (33.9 cu. ft. per hour) in the upper part of the reactor at 1,700° F. The average distance between the suspended particles, if they are assumed to be spherical and have an average diameter of about 0.21 mm., is approximately 6 mm. The latter value thus estimated is analogous to the term "mean free path," although used here in a different sense.

As shown in Figure 1, the residue and product gas recovery system is at the bottom of the reactor tube. The solid residual is collected in a receiver bottle, and is cooled, weighed and analyzed. Most of the excess steam and some fine soot collects in the condensate receiver; the rest of the soot is removed from the gas by means of a wash bottle. Traces of tar vapors in the product gas are caught on filter papers in a Buchner funnel, and the gas is metered, sampled, and vented.

A photograph of the apparatus is shown in Figure 2. Next to the control board in the foreground, the insulated reactor tube is seen with the product recovery train below it. The fuel-feeding and steam-generating systems are located on the upper platform partly visible at the top of the picture.

As the reactivity of powdered or granular fuel is affected by the size of the particles, it was necessary to investigate possible degradation of particles as they fall through the reactor-tube. Do the solid fuel particles abrade each other and, if so, is this size reduction balanced, in case of bituminous coals, by swelling of the particles when they pass through the plastic stage, usually between 700° F. and 1,000° F.? To answer these questions, the apparent (or bulk) specific volumes of two different coals and a char were determined, before and after a single passage through the reactor under the usual conditions at 1,700° F. Specific volumes were determined by filling a 10-cc. graduated cylinder with the particles, uniformly tapping, and then weighing the contents. The results are shown in Figures 3 and 4 with the apparent (bulk) specific volume in each case given below the photomicrograph of the sample. The specific volume data shown on these pictures are helpful in this evaluation since any increase in the apparent (bulk) specific volume or, conversely, decrease in bulk density may be due to (1) formation of fines (degradation), and/or (2) swelling of each particle with corresponding increase in porosity.

In addition to the microscopic examinations, the extent of degradation in fall was determined by drop-testing samples (-60 + 65 mesh per inch size) through the reactor-tube, in still air, at room temperature. A Wyoming high-volatile bituminous-C

coal (Serial No. 16) and a char, made by low-temperature carbonization from a Colorado bituminous-A coal, (Serial No. 7), were so tested for size degradation. In each case the procedure was identical: 100 grams of the sample was dropped 123 inches at a rate of 72 grams per hour (1.2 g. per min.), and the product was screened through a 65-mesh per inch standard screen, uniformly shaking and tapping it in each case. The results were negative. In both cases the size degradation was small, although the char was somewhat more resistant to breakage than the coal. The breakage index, which is the percent retained on the 65-mesh screen before the drop-test minus that retained after the drop-test, was 1.7 percent for the coal and 0.2 percent for the char. The time of fall during the drop-tests, determined visually, was 4.4 seconds for the coal and 3.5 seconds for the char.

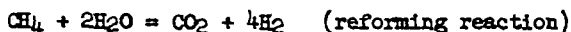
These results confirm what is evident from Figures 3 and 4: any size degradation from attrition of the particles by themselves and by the reactor wall is negligible and is well within the expected experimental error. Even this slight size reduction is more than balanced in the case of bituminous coals by the swelling of the particles as they pass through the plastic stage. There is plenty of evidence of swelling and formation of hollow spheres, as shown by the photomicrographs in Figures 3 and 4, as well as by the considerable increase in bulk specific volumes.

Experimental Fundamentals

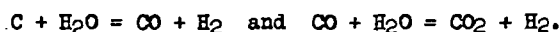
Tests to determine the relative reactivities of coals were carried out under as nearly identical conditions as possible, thus maintaining at all times the major operating variables as constant as practicable. The most essential variables affecting the reactivities of powdered coals are: (1) type and size of test-reactor; (2) type, chemical composition and microstructure (porosity) of the coal; (3) particle size of the coal, its size consist and density; (4) coal throughput; (5) steam input rate (or steam-to-coal weight-ratio); (6) residence (or contact) time; (7) temperature; and (8) pressure. In developing a rapid practical method for testing coals for reactivity, the objective was to establish the correct magnitude for these variables in order to obtain measurable, but not excessive, fuel and carbon conversions.

An important variable in need of study was the required steam-to-coal ratio. The results of this study are illustrated in Figures 5 and 6. Figure 5 shows the effect of steam concentration (in terms of steam-to-carbon weight-ratios) on the components of the gases evolved. The yields of gases are seen to increase with increasing steam-to-carbon ratios, but most of the increase in the total gas yield was due to the rising trend in hydrogen evolution. This interesting fact points to a possible interaction of steam with hydrocarbon groups and other radicals attached to the coal molecule, and it appears that the interaction increases with the steam concentration. Although the diagram in Figure 5 refers to a low-volatile bituminous coal, yield curves showing identical trends were obtained with high-volatile bituminous coals.

The interaction of steam appears to facilitate thermal decomposition at a lower temperature, causing the detachment of alkyl groups and other radicals from carbon atoms in the coal matrix. This may result in the formation of "defect sites," probably with an electron lost or removed from the carbon atom from which a radical (possibly in ionic state) was detached. The existence of such defect sites owing to electron absences (or "positive holes") has been recognized by Gray (6) and his co-workers. The methane, ethane, other paraffin hydrocarbons, carbon monoxide, etc., thus entering the gas phase may react with additional steam to form CO_2 and H_2 . For example:



This is a plausible explanation of the hydrogen evolution (Figure 5) accompanying the interaction of steam with the coal molecule. There is plenty of evidence that steam thus interacts with coal both in carbonization and gasification, i.e., whenever thermal decomposition of coal takes place in the presence of steam (14). The defect carbon sites, often called "reaction sites" or "active sites," thus formed are vulnerable to attack by steam:



The importance of steam-to-carbon ratio thus established, experiments were made to determine its effect on the reactivity, measured as fuel or carbon conversion. Figure 6 shows that for both high and low volatile coals the reactivity rises asymptotically up to a ratio of about 3:1. Above this ratio, additional steam does not significantly increase the carbon conversion, i.e., a maximum has been reached. A ratio of 3:1 was thus chosen, as too much excess steam would increase the flow-rate, thereby decreasing the contact time below the limit of effective conversion needed for most of the reactivity tests.

Similarly, accurately measurable conversion was the criterion used in determining or choosing the optimum values of other essential variables. Thus, all of the tests were made with coals closely sized to pass a 60-mesh per inch U. S. standard sieve but retained on a 65-mesh sieve. The coal-feed rate was fixed at about 50 grams per hour and kept as constant as possible throughout each test. The temperature was kept uniform throughout the 83-inch long isothermal zone between 1,650 and 1,750° F., the maximum variation being $\pm 25^\circ$ F. The average residence time of the coal particles in the isothermal zone ranged from 5.2 seconds for subbituminous and low or high-volatile bituminous coals to 6.6 seconds for anthracites. (The determination of these values by an isotope-tracer method will be discussed by the authors in a future paper.)

The optimum values for the variables, thus determined, were kept as constant as possible so that the results of the reactivity tests depended only on the type, composition, and microstructure of the coal tested.

Materials Tested

Descriptions of the types of fuels tested for their reactivities are given in Table 1. The coals are presented in the order of increasing rank, ranging from lignites to anthracites. Also included in Table 1 are several types of chars derived by low-temperature carbonization from the specific types of coals shown in the table. Although the reactivities of these chars were determined in the same apparatus by the same technique described above for coals, the objective of the work with chars was sufficiently different to merit separate discussion in a future paper.

Proximate and ultimate analyses of the fuels tested are shown in Table 2 on a dry, "mineral matter - free" basis. Included in this table are in each case the percent mineral matter, calculated in conformity with ASTM standards (1) and the C/H ratio. Use of the "mineral matter - free basis" resulted in a much better alignment of data along the curves shown in various diagrams representing the functional relation between reactivity and various coal constituents or ratios.

Results and Discussion

Usually two, but in some cases up to five, reactivity tests were made on each of the 12 types of coals listed in Tables 1 and 2. The test results for each batch of coal were averaged and plotted on the following diagrams.

All of the reactivity test data (including data on several chars produced by low-temperature carbonization at the Bureau of Mines Denver Coal Research Center from

some of the coals investigated) are shown in Figure 7. This diagram illustrates the relative reactivities, in terms of fuel conversion, of coals of various rank (geological age) and their corresponding chars (connected with broken lines and arrows), as a function of steam concentration. Expressed on dry, mineral matter - free basis, coals of the same rank fall approximately along straight lines, each line indicating a given reactivity level. Most of the lines tend to be horizontal or slightly upward sloping and are usually parallel. The deviations in slopes, however, may not be significant owing to experimental errors in analyses or sampling. Actually, they should slope slightly upward, as in Figure 6, although for the shorter range of steam-to-coal weight-ratios, 2.2 to 3.5 shown in Figure 7, the upward trend is not as noticeable.

In general, it may be concluded that the reactivities of coals are inversely proportional to their rank or geological age. From this it follows that the reactivity is a function of the chemical composition and microstructure (porosity, density, etc.) of the coal as these, in turn, depended on the type of vegetation and geologic factors that existed when the coal beds were formed in various prehistoric ages. Since coals of various rank characteristically differ in volatile matter --- the ASTM (1) classifies them into ranks largely on the basis of volatile matter (on mineral matter - free basis) and calorific value --- it is evident that the reactivity must be related to the volatile matter as determined by the standard ASTM test. However, volatile matter and gas yield measured in reactivity tests are related terms, although by no means are they identical. The volatile matter test is intended to duplicate, to some extent, coke oven conditions in small-scale carbonization in a crucible at 950° C. (1,740° F.); the reactivity test is a combination of carbonization and gasification in steam medium at about 1,700° F. The gas yield, therefore, does not include the water formed as a result of carbonization, but it does include the product gases resulting from the steam-carbon reaction (CO , CO_2 , and H_2) to the extent that this reaction takes place at 1,700° F. When fuel conversion is plotted versus volatile matter (Figure 8) and against gas yield (Figure 9), similar S-curves result, but the latter curve is much steeper. The significance of this difference is subject to further interpretation with additional experimental evidence on hand.

Thus, as has been claimed by several investigators (13), the reactivities of coals of various rank and type are functions of the volatile matter as determined by the standard ASTM test. Yet, the functional relation is not linear, as claimed in the past with considerable deviations admitted, but a mild-sweep S-curve, as shown in Figure 8.

While volatile matter has served for some time as an approximate, although auxiliary, index of rank, the results of this investigation show that the total carbon content and C/H ratio are more sensitive indicators of the ranks of coals. In plotting the reactivity against the carbon in coals, it was found that both the fuel and carbon conversions are cubic parabolic functions of the total carbon content. When plotted on mineral matter - free basis, not a straight line but a well-defined S-curve is obtained (see Figure 10). The reactivity decreases with increasing carbon content, very rapidly in case of younger coals, much more slowly with h.v. bituminous coals, and rapidly again in case of l.v. bituminous coals and anthracites.

On the other hand, the reactivities of coals, expressed in terms of either fuel or carbon conversion, are nearly perfect hyperbolic functions of the carbon-to-hydrogen weight-ratio (C/H), as shown in Figure 11. This appears to be significant both from the standpoint of fuel classification and process engineering, i.e., selection of coals for effective gasification. The C/H ratio appears to be an excellent indicator of rank, and may also be an indicator of the quality of synthesis gas, or that of high-B.t.u. gas or liquid fuel that can be produced by gasification and subsequent synthesis. In spite of this, it is not suggested that either the volatile matter, or total carbon content, or C/H ratio could be used as the sole index of rank.

An entirely different method of plotting the reactivity data is presented in Figures 12 and 13. The purpose of these diagrams was to determine the extent of the

reactivity, in terms of fuel conversion, caused by (1) thermal decomposition (devolatilization) and (2) the actual steam-carbon reaction. The effects of these two factors overlap in the reactivity tests described. We can say with considerable certainty that each particle of coal thermally decomposes with the evolution of volatile matter as its temperature rises to 1,700° F. The steam thereupon reacts with carbon atoms deprived of hydrocarbon, hydroxyl, carboxyl, and other side chains, i.e., it reacts with the so-called "fixed carbon." As the volatile matter evolved in thermal decomposition consists of much volatile carbon (in the form of CH_4 , CO_2 , CO, etc.), the fixed carbon remaining is always numerically less than the total carbon in the coal. Thus, if we deduct the percent of volatile matter (i.e., grams of coal converted to gas per 100 gram sample), as determined by the ASTM test at 1,740° F. (950° C.), from the fuel conversion (in terms of grams of coal converted to gas per 100 gram sample) at about 1,700° F., the difference will be the percent fixed carbon that reacted with steam to form CO, CO_2 , and H_2 . The two temperatures, 1,740° F. and 1,700° F. are sufficiently close to permit the approximation.

An interesting observation can be made and conclusion drawn by examining closer the diagram in Figure 12 on the reactivity of fixed carbon in relation to the total carbon content of coals of various rank. It shows that the actual steam-carbon reaction generally decreases with increasing order of rank from lignites to anthracites. However, a similar plot of conversion by the steam-carbon reaction alone versus the fixed carbon content (Figure 13) shows more clearly than the previous diagram that the rapidly descending curve tends to become asymptotic beyond 65 percent fixed carbon on dry mineral matter - free basis. In other words, steam at 1,700° F. reacts with carbon in younger coals with surprising ease, but less and less easily with carbon in older coals of increasing rank, while the carbon in coals from h.v. bituminous rank to anthracites is nearly equally reactive.

The conclusion drawn is significant, yet understandable in light of the explanation given above under Experimental Fundamentals. Lignites and other young coals have many more alkyl side chains and several other radicals attached to the benzenoid coal matrix than older bituminous coals, and still less in anthracites. When these radicals crack off the carbon atoms as a result of the interaction of steam, the "defect" sites remaining are vulnerable to attack by H_2O molecules, which explains the decreasingly lower reactivities of coals from lignites to anthracites.

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Table 1

DESCRIPTION OF TYPES OF FUELS TESTED FOR THEIR REACTIVITIES

Serial No. 1/	Rank of coal *Type of char	Name of bed	Mine	Locality
1	Young Lignite			Sandow, Texas
2*	Char made from Texas lignite (Serial No. 1)	Carbonized at 930° F. with an air-to-coal ratio of 3.73 std.cu.ft/lb. maf coal.		
10	Older lignite	Healy	Reynolds	Lake de Smet Area, Buffalo, Johnson County, Wyoming
12*	Char made from Lake de Smet lignite (Serial No. 10)	Carbonized at 930° F. with an air-to-coal ratio of 4.01 std.cu.ft/lb. maf coal.		
3	Subbituminous-B coal	Adaville No. 1	Elkol Kemmerer Coal Co.	Hams Fork Region, Frontier, Wyo.
16	High-volatile coal bituminous-C	No. 7 Seam	D. O. Clark	Superior, Wyoming
11	High-volatile coal bituminous-C	Rock Springs No. 3	Sweetwater No. 2	Green River Area, Wyoming
4	High-volatile coal bituminous-A	Pittsburgh	Pittfair	Shinnston, W. Va.
5	High-volatile coal bituminous-A	Sewickley	Bunker	Monongalia County, West Virginia
6	High-volatile coal bituminous-A	East Allen	East Allen	Garfield County, Colorado
7*	Char made from Colo. bituminous-A coal (Serial No. 6)	Carbonized at 1,200° F. with an air-to-coal ratio of 13.9 std.cu.ft/lb. maf coal.		
13*	Char made from Colo. bituminous-A coal (Serial No. 6)	Carbonized at 1,200° F. with an air-to-coal ratio of 6.9 std.cu.ft/lb. maf coal.		
15	Medium-volatile bituminous coal	Sewell	Wyoming	Wyoming, West Virginia
8	Low-volatile coal semibituminous	Pocahontas No. 4	Island Creek Coal Co.	McDowell County, West Virginia
9	Anthracite		Penn. & Reading Coal and Iron Co.	Locust Summit, Pennsylvania
14	Anthracite		Underkoffers	Iykens, Dauphin County, Penna.

1/ The serial numbers shown identify the type of fuel tested in subsequent tabulations and diagrams. All coals are shown in the order of increasing rank. An asterisk next to the serial number signifies char. See the corresponding heading above for coals and chars, respectively.

Table 2

ANALYSES OF FUELS TESTED

Serial No. 1/	Type of fuel	Mineral matter in fuel, percent	Components, percent mineral matter-free basis							C/H Ratio
			V.M.	F.C.	C	H	O	N	S	
1	Young Texas lignite	15.7	48.8	51.2	72.9	5.5	18.6	1.4	1.6	13.3
2*	Char made at 930° F.; air-to-coal ratio: 3.72/	20.8	32.5	67.5	77.0	5.8	16.2	1.7	1.5	20.5
10	Older Wyoming lignite	20.0	46.4	53.6	71.7	4.8	22.1	1.0	.4	14.9
12*	Char made at 930° F.; air-to-coal ratio: 4.02/	26.8	29.9	70.1	78.1	3.4	16.2	1.2	1.1	23.0
3A	Wyo. subbituminous-B coal, Adaville No. 1 bed	3.4	42.2	57.8	74.2	5.0	18.8	1.3	.7	14.8
B		3.1	42.5	57.5	73.2	5.2	19.9	1.2	.5	14.1
16	Wyo. high vol. bituminous-C coal, No. 7 bed	3.8	40.4	59.6	78.3	5.3	14.2	1.3	.9	14.7
11	Wyo. high vol. bituminous-C coal, Rock Springs, No. 3 bed	12.1	32.2	67.8	82.8	5.5	9.1	1.8	.8	15.1
4	W. Va. high v. bituminous-A coal, Pittsburgh bed	11.3	38.2	61.8	81.7	5.9	7.2	1.6	3.6	13.9
5	W. Va. high v. bituminous-A coal, Sewickley bed	15.6	39.9	60.1	82.3	5.9	8.0	1.6	2.2	14.0
6	Colo. high v. bituminous-A coal, East Allen bed	24.0	37.3	62.7	83.7	6.2	7.9	1.7	.5	13.5
7*	Char made at 1,200° F.; air-to-coal ratio: 13.92/	49.2	5.1	94.9	82.5	2.7	12.3	1.9	.6	30.6
13*	Char made at 1,200° F.; air-to-coal ratio: 6.92/	31.3	5.7	94.3	92.2	2.0	3.2	1.7	.9	46.1
15	W. Va. medium vol. bituminous coal, Sevell bed	2.8	20.7	79.3	89.5	4.7	3.5	1.6	.7	18.9
8A	W. Va. low vol. semibituminous coal, Pocahontas	5.2	14.0	86.0	91.0	4.4	2.8	1.3	.5	20.7
B	No. 4 bed	5.5	13.8	86.2	91.2	4.4	2.6	1.3	.5	20.7
9A	Pennsylvania anthracite from Locust Summit, Pa.	14.2	5.8	94.2	91.9	2.8	3.7	1.0	.6	32.8
B		15.5	4.8	95.2	91.8	3.2	3.3	1.1	.6	28.7
14	Pennsylvania anthracite from Lykens, Pa.	13.3	5.7	94.3	92.2	3.4	2.3	1.2	.9	27.1

1/ Designations A and B represent the analyses of different batches of the same coal.
An asterisk next to the serial number signifies char.

2/ Air-to-coal ratios are based on std. cu. ft. air injected per lb. of coal carbonized.

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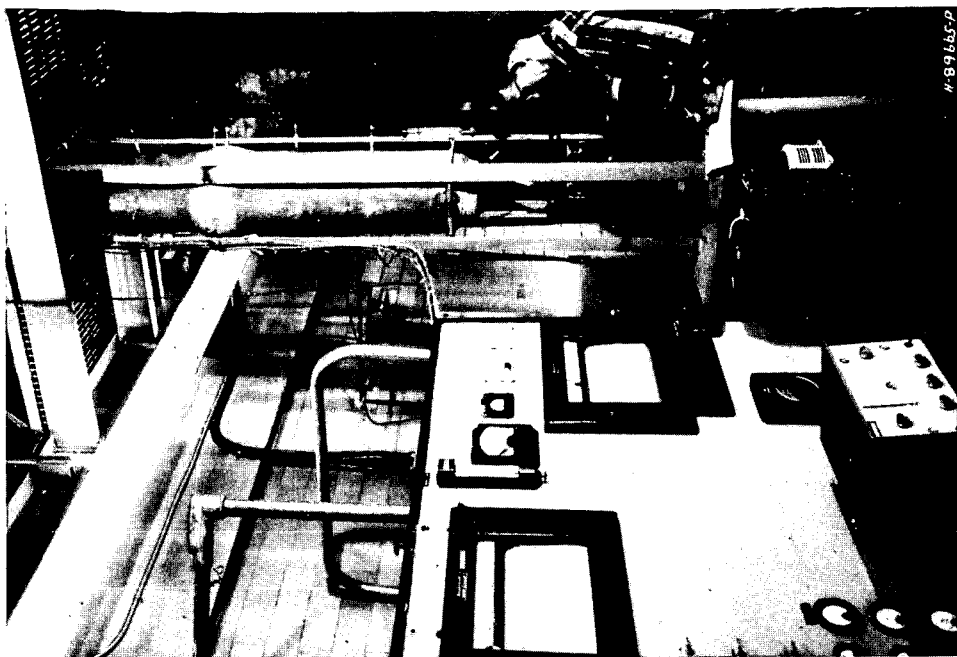


Figure 2. Photograph of Apparatus used for Study of the Kinetics of Reactions of Coals and Chars with Steam.

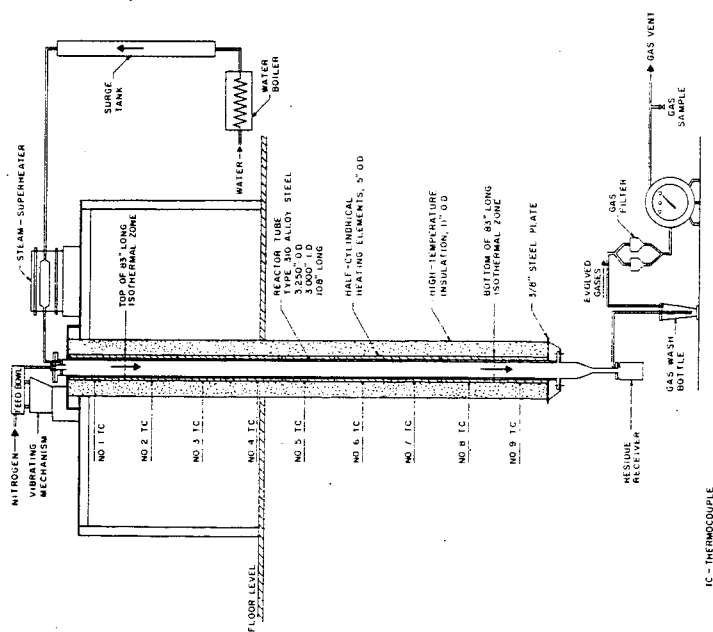
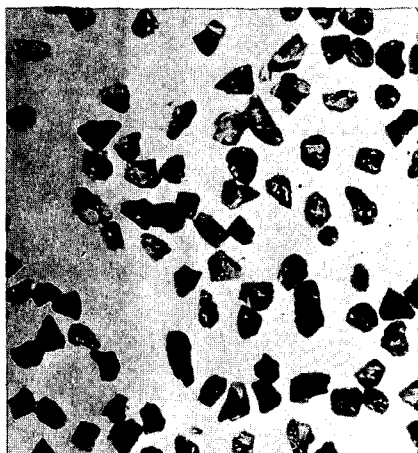
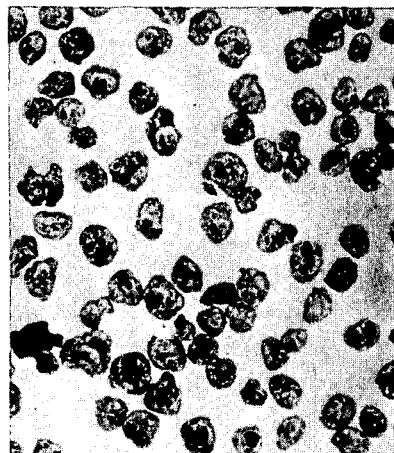


Figure 1. Isothermal Reactor for the Study of the Kinetics of Steam-Coal Reaction at High Temperatures



No. 11 - Wyoming H.V. Bituminous-C coal.
Size: -60 + 65 mesh/in; sp vol:
1.39 cm³/g



No. 11-R - Single pass residue obtained
from testing No. 11 coal.
Sp vol: 4.13 cm³/g

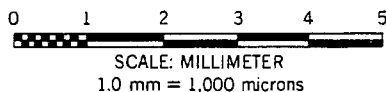
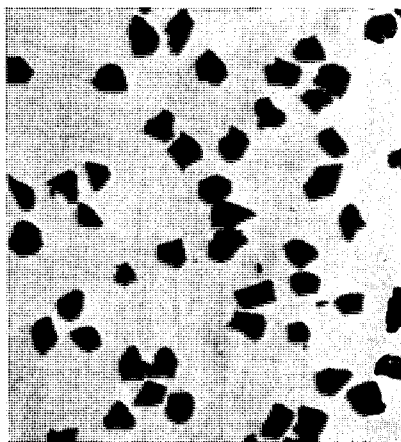


Figure 3. Photomicrographs of a Bituminous-C Coal and its Residue from Reactivity Test made at 1,700° F in Steam Medium (approximate enlargement 17X).



No. 6 - Colorado H.V. Bituminous-A coal.
Size: -60 + 65 mesh/in; sp vol:
1.32 cm³/g



No. 6-R - Single pass residue obtained
from testing No. 6 coal.
Sp vol: 2.99 cm³/g

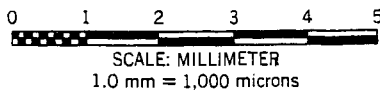


Figure 4. Photomicrographs of a Bituminous-A Coal and its Residue from Reactivity Test made at 1,700° F in Steam Medium (approximate enlargement 17X).

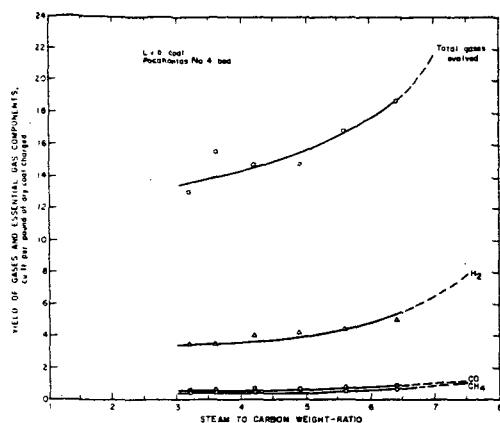


Figure 5. Effect of Steam Concentration on Gas Yield, 1700° F

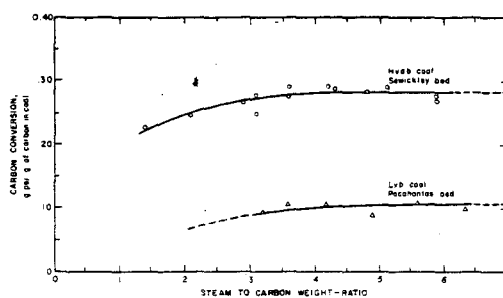


Figure 6. Effect of Steam Concentration on Carbon Conversion, 1700° F

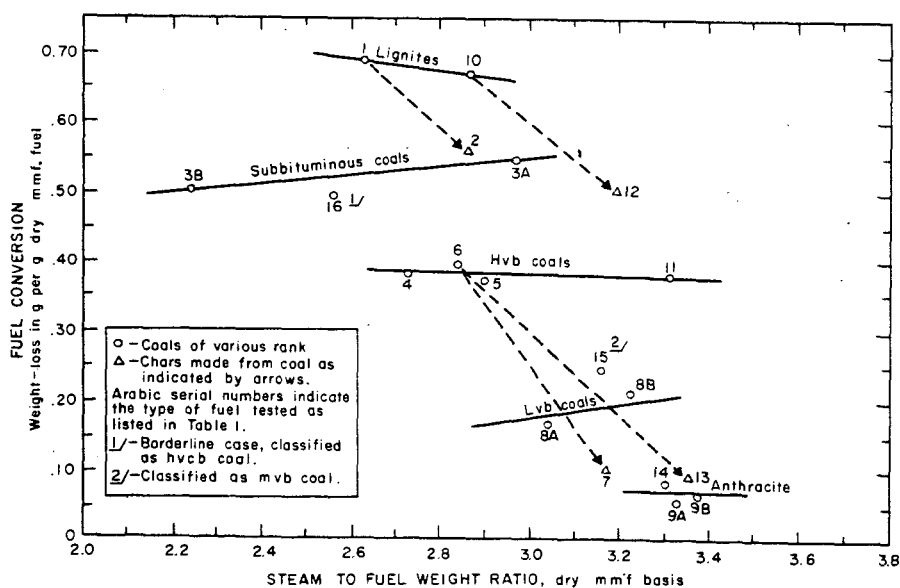


Figure 7. Comparative Reactivities of Coals and Chars

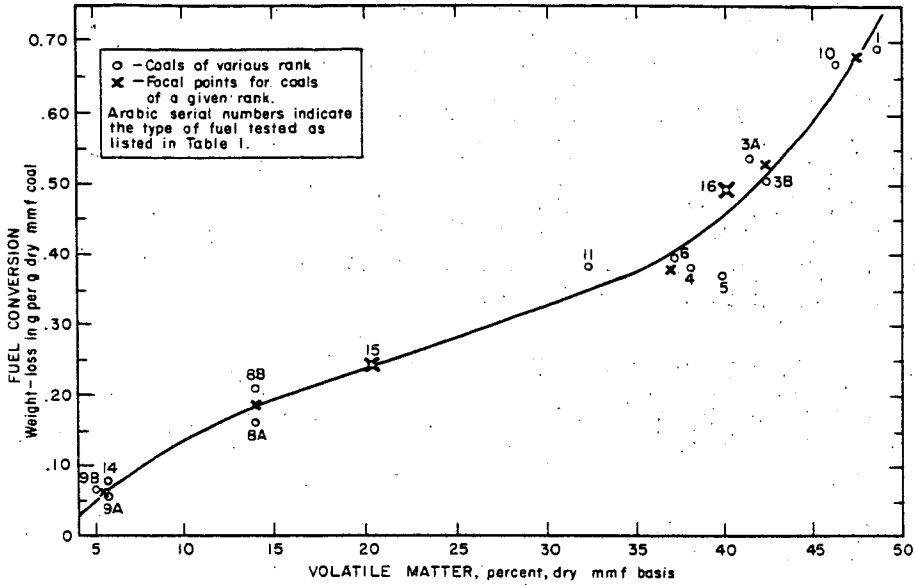


Figure 8. Fuel Conversion as a Function of Volatile Matter
— Steam Reacting with Coals at 1700° F

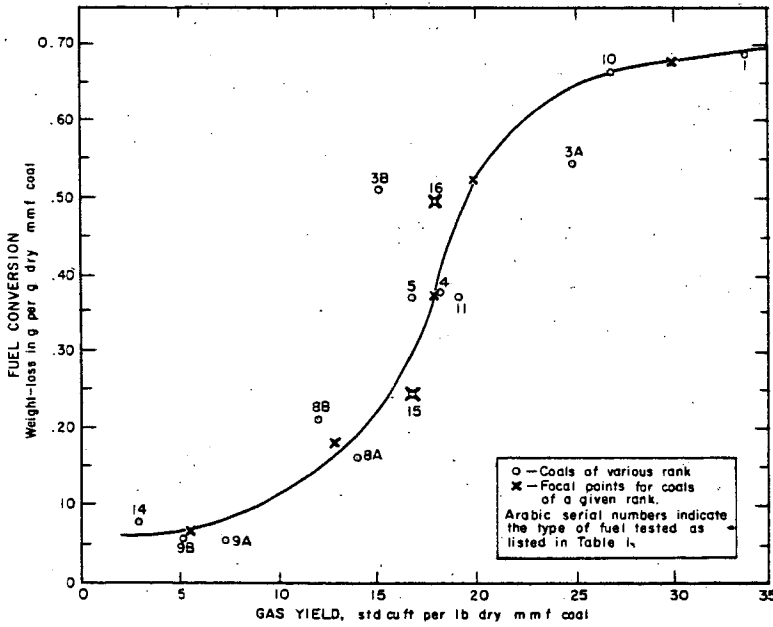


Figure 9. Relation Between Fuel Conversion and Gas Yield
— Steam Reacting with Coals at 1700° F

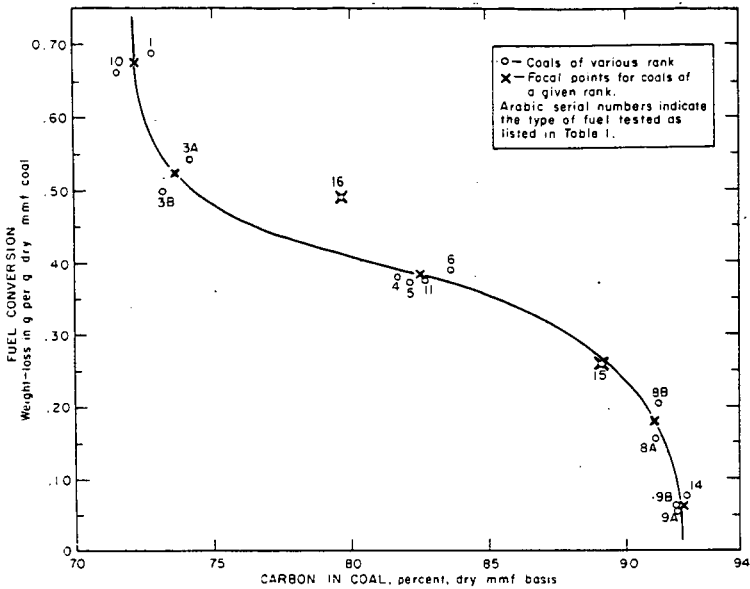


Figure 10. Fuel Conversion as a Function of Carbon Content
— Steam Reacting with Coals at 1700° F

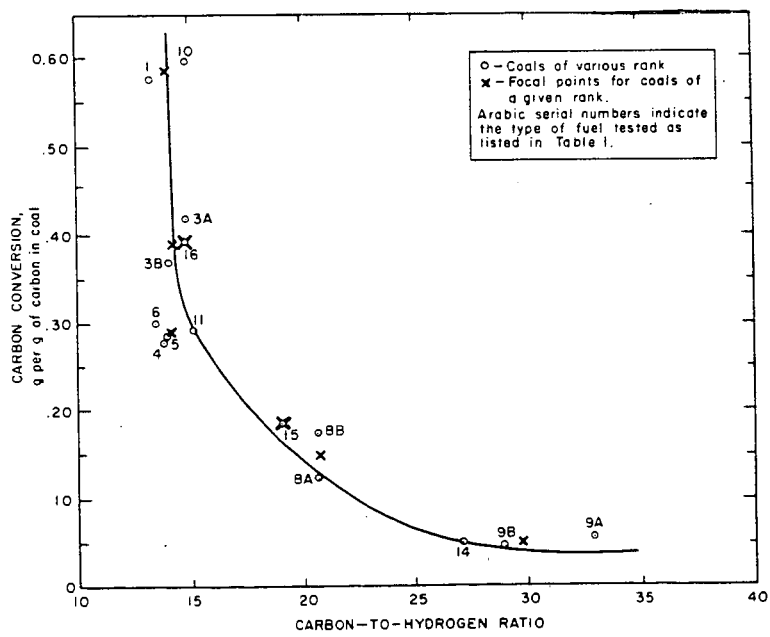


Figure 11. Carbon Conversion as a Function of Carbon-to-Hydrogen Ratio
— Steam Reacting with Coals at 1700° F

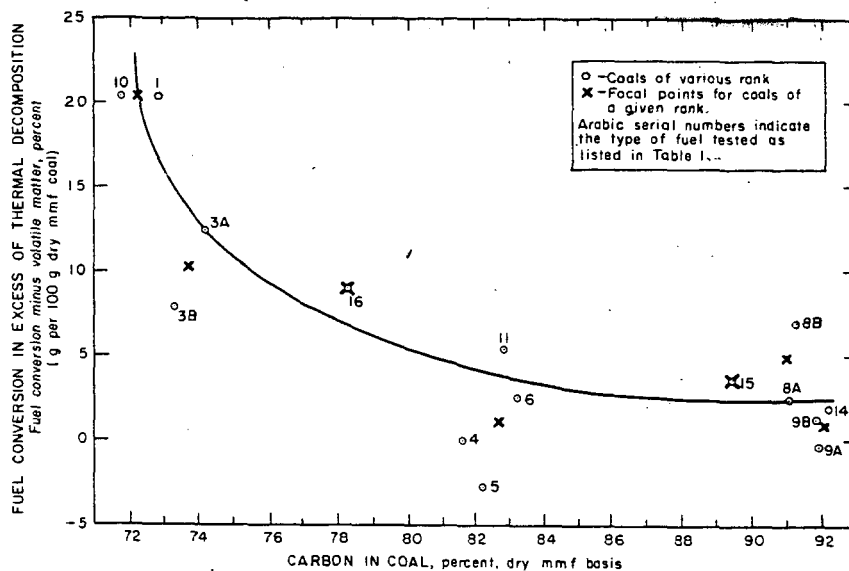


Figure 12. Relation Between Total Carbon in Coal and the Reactivity of Fixed Carbon — Steam Reacting with Coals at 1700° F

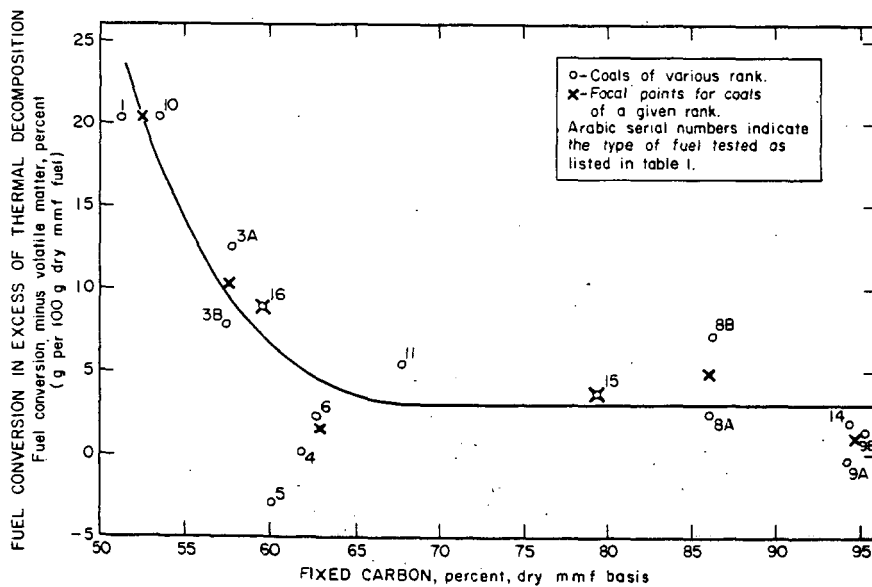


Figure 13. Relation Between Fixed Carbon in the Coal and the Reactivity of Fixed Carbon — Steam Reacting with Coals at 1700° F